Tests of Gravity with Lensing, Galaxies and Large Scale Structure

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References

Jain & Zhang (2007) arXiv:0709.2375

Hoekstra & Jain (2008) arXiv:0805.0139

Stabenau & Jain (2006) arXiv:0604038

Outline

- Modified gravity scenarios
- Light deflection in modified gravity
- Combining cosmological observables to test gravity
- Tests of gravity on galaxy and cluster scales

Modified gravity theories

Cosmic acceleration may be due to dark energy or to a modification of the Friedman equation

Goal: "Weaken" gravity at late cosmic times and large scales

Alternate gravity theories are not easy to construct!

And they must pass early universe and solar system tests

Types of theories:

$$H^2 - \frac{H}{r_c} = \frac{8\pi G}{3}\rho$$

- Higher dimensional theories, e.g. DGP:
- Additional terms in the action: f[R]:, e.g. powers of R or 1/R

Constraints on Gravity

Below 1 AU

- Lab tests on mm scales
- Solar System: lunar ranging
- Binary pulsar

1Kpc-1 Mpc

- 1-50 Kpc: Galaxy rotation curves, velocity dispersions
- 50-500 Kpc Satellite galaxy dynamics
- 50 Kpc-10 Mpc Galaxy-galaxy lensing
- 100 Kpc-1 Mpc Galaxy clusters: X-Ray-Dynamics-Lensing

10-1000 Mpc

- Large-scale structure: current constraints are weak, model-specific

Early universe: Nucleosynthesis, CMB

Testing gravity on large scales

- Homogeneous solution must give correct distance-redshift relation: assume *H(z)* matches Λ-CDM

- The relation of perturbed observables to *H(z)* may be altered:

  - Metric potentials ϕ and ψ

  - Density and velocity perturbations δ and $\theta = \nabla \cdot v$ (from $\delta T_{\mu\nu}$)

- The perturbed variables are altered at low z and large scales.

  ➡ Large-scale structure observables must be completely re-interpreted!

- Their behavior approaches GR on solar system scales. Where the transition occurs is largely unknown (10kpc-10Mpc?).

Growth Factors in Modified Gravity

$$ds^2 = -(1+2\psi)dt^2 + (1-2\phi)a^2(t)d\mathbf{x}^2$$ **Metric**

$$\nabla^2(\psi+\phi) = 8\pi G_{eff} a^2 \bar{\rho}\delta$$ **Poisson**

$$\eta = \psi/\phi$$

η and G_{eff} can be scale and time dependent in modified gravity

$$\delta'' + 2H\delta' - \frac{8\pi G_{eff}}{1+1/\eta}\bar{\rho}a^2\delta = 0$$

Different growth factors for density and metric potentials:

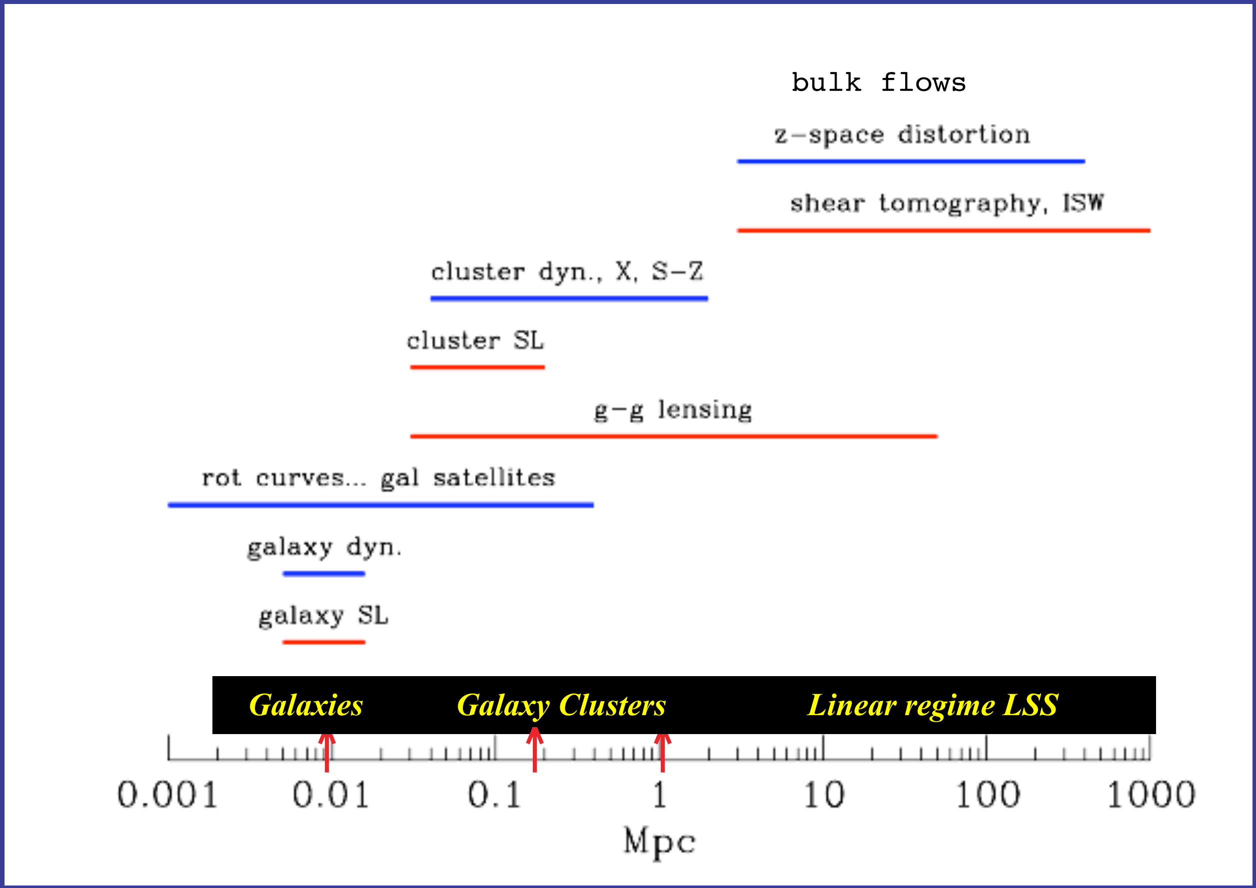
– Density growth factor: $\mathbf{D}_\delta(z,k)$

– Lensing growth factor: $\mathbf{D}_{\psi+\phi} \propto G_{eff}\, \mathbf{D}_\delta$,

– Dynamical growth factor $\mathbf{D}_\psi = \eta/(1+\eta)\, \mathbf{D}_{\psi+\phi}$

Jain & Zhang 07; Hu & Sawicki 07, 08; Zhang et al 07; Bertschinger & Zukin 08…

Probes of metric potentials



Dynamical probes (blue) measure Newtonian potential ψ

Lensing and ISW (red) measures $\phi + \psi$

Constraints from current data are at 10-50% level *(w/ Guzik… in prep.)*

Modified gravity: Sociology

Astronomers ***bitter*** with **Dark Energy**-driven cosmology (and reportedly clinging to their favorite galaxy) can cheer up at the prospects of testing gravity.

- The internal dynamics and lensing properties of galaxies and clusters matter! **Fundamental physics** can be advanced without disparaging galaxies as convenient **points** (BAO snobs) or **wallpaper** (lensing elites).

- Observables are valuable even if their **Fisher forecasts** for Ω and w are not the very best (e.g. ISW, bulk flows).

*Will modified gravity be the reconciler of **blue-collar** astronomers and **elitist, 'fundamentalist'**(arxiv:0704.2291) cosmologists?*

- Will string theorists, who find our 3-dimensional universe so imperfect, now be found palin' around with Joe the astronomer?
- Must we "redistribute the wealth" to diverse experimental approaches in order to make progress - socialist cosmology anyone?

You betcha!

- Modified gravity scenarios
- Lensing: light deflection in modified gravity
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Lensing: what we assume about gravity

- Deflection angle formula $\alpha \overset{\textbf{GR}}{=} -2\, \nabla_\perp \phi_{2d}$ from Geodesic eqn

Generalize ➡ $\alpha = -\nabla_\perp (\phi + \psi)_{2d}$

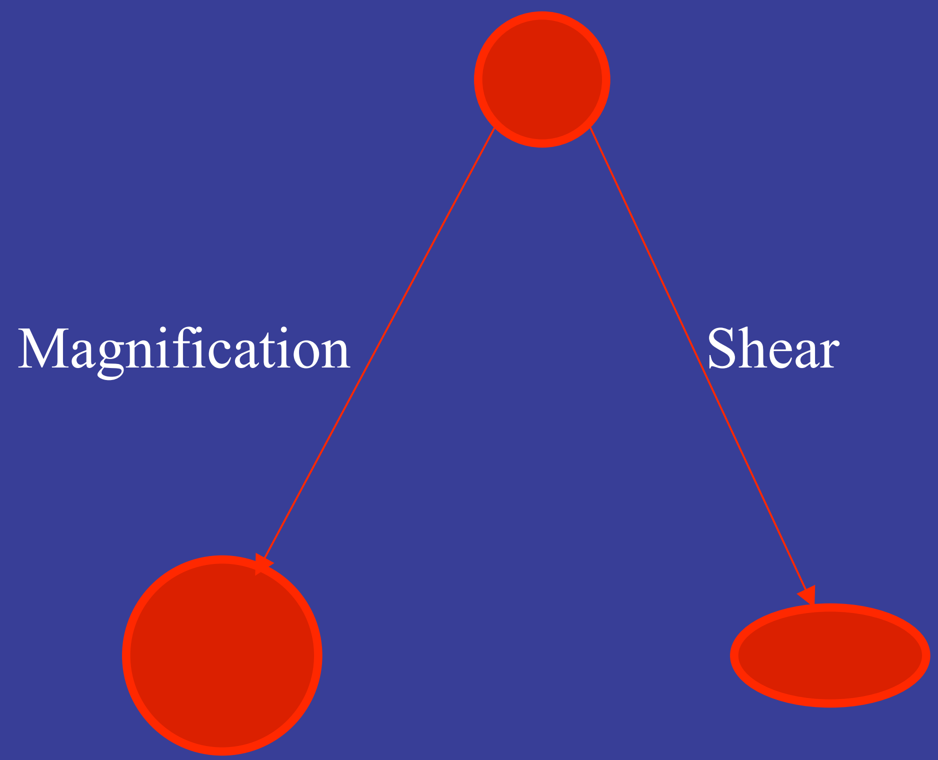
- How the observable convergence κ is related to mass fluctuations:

$$\kappa \equiv \tfrac{1}{2}\left(\partial_1{}^2 + \partial_2{}^2\right)(\phi + \psi)_{2-d} \overset{\textbf{GR}}{=} G\bar{\rho} \int dz\, W(z, z_s)\delta(z)$$ Poisson eqn

Generalize ➡ $\bar{\rho} \int dz\, G_{eff} W(z, z_s)\, \delta(z)$

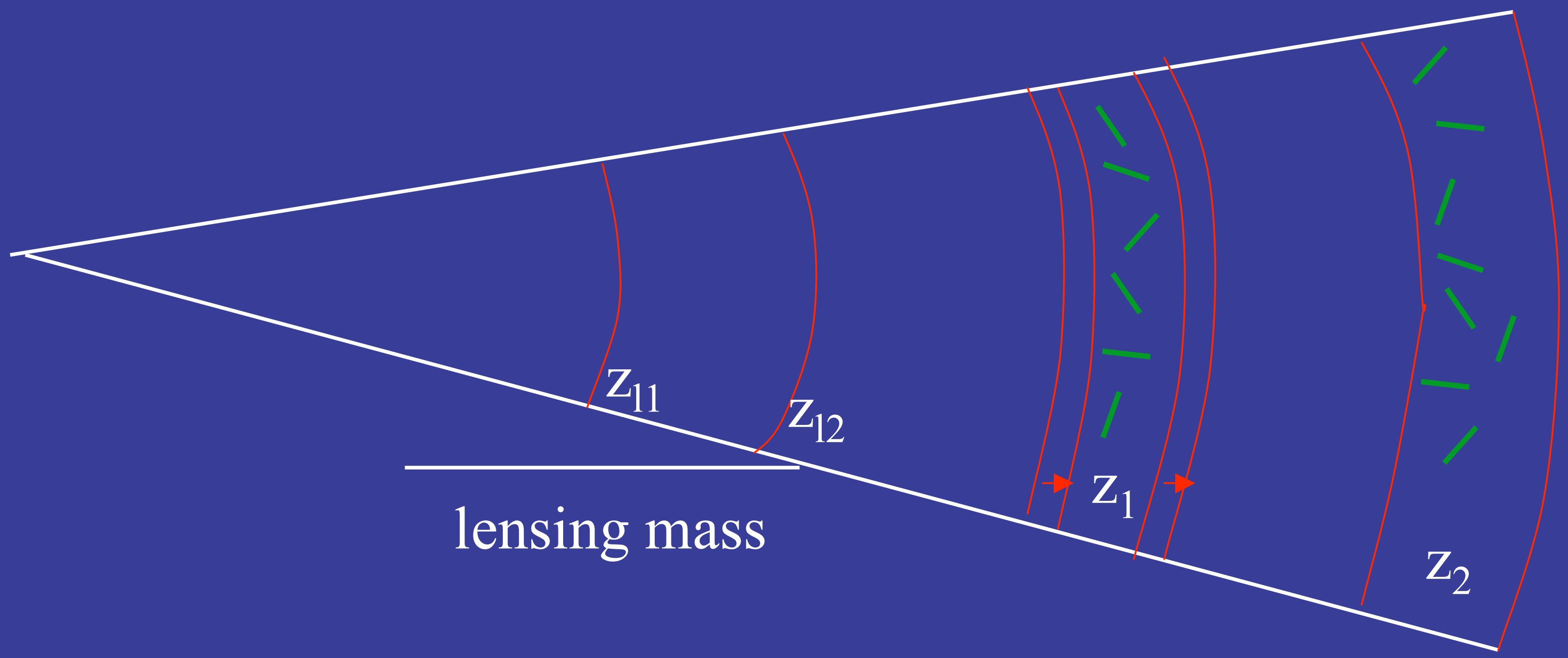
- The geometric factor $W(z, z_s)$ can be taken as fixed.

Magnification and Shear



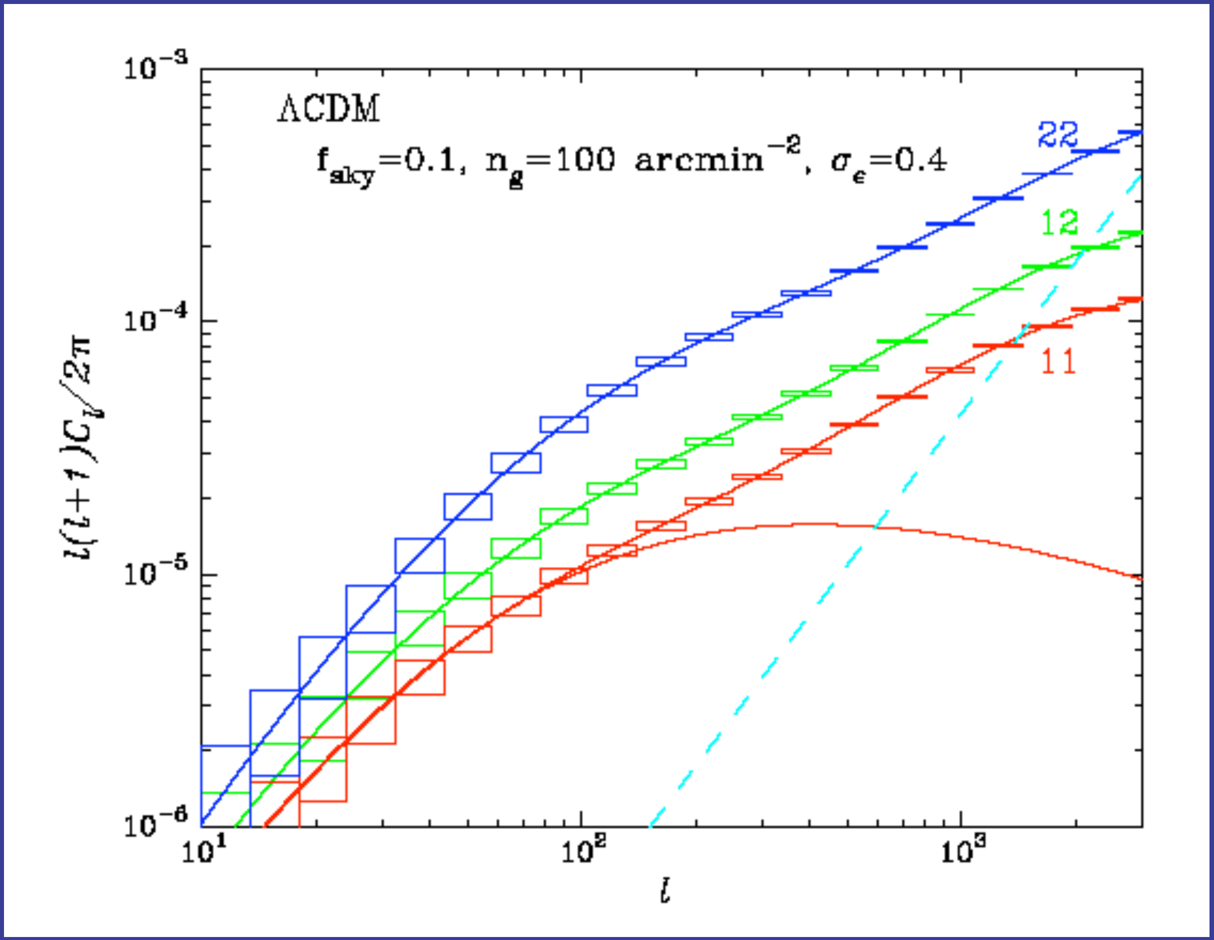
Weak lensing ➡ Magnification ≅ Convergence (projected mass density)

Lensing tomography



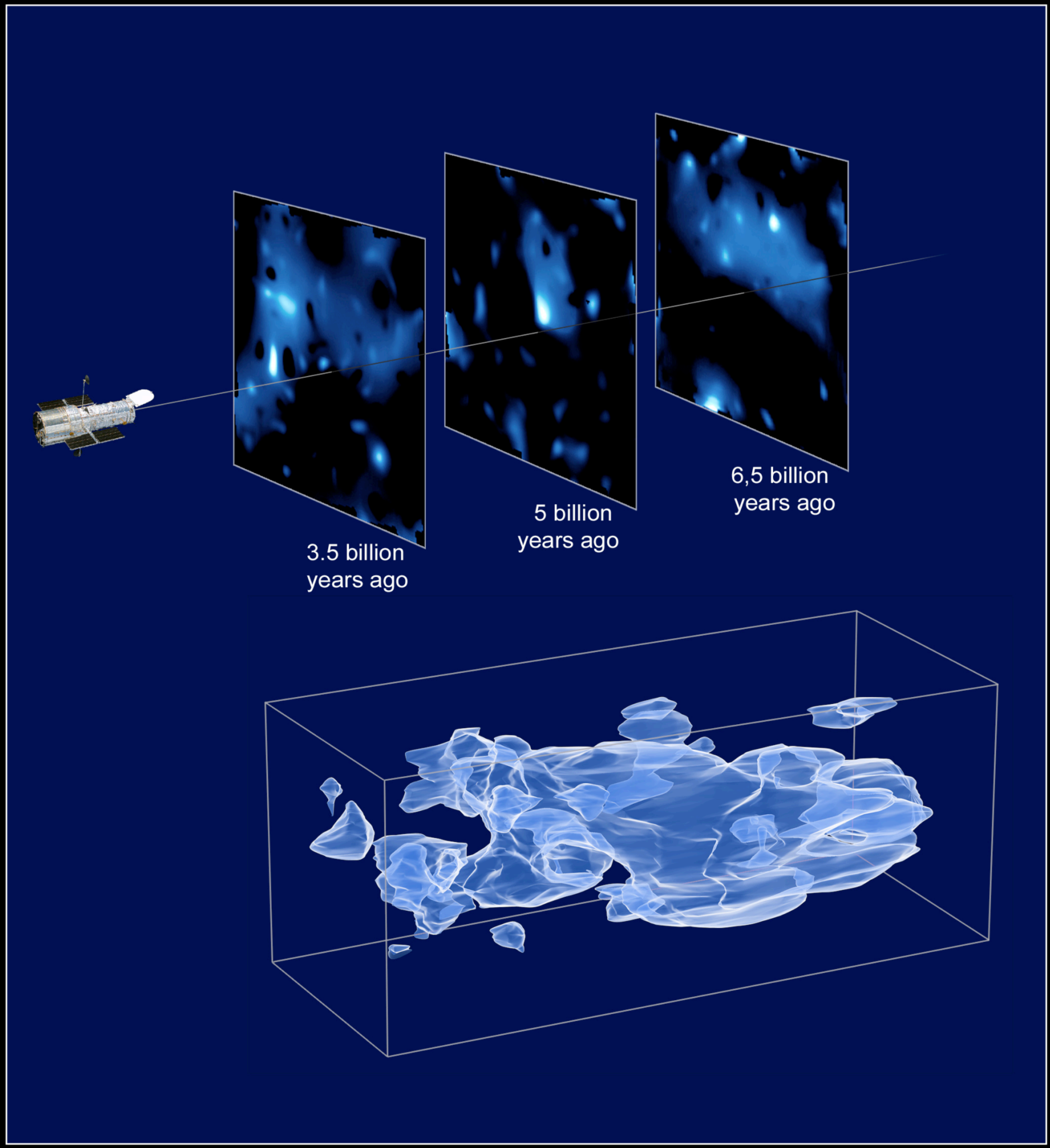
Shear at z_1 and z_2 given by integral of growth function & distances over lensing mass distribution (Hu 1999)

Lensing power spectrum



The theorists version of a future lensing measurement

Takada & Jain 2004



Massey et al 2007

How does lensing test gravity?

- By itself, lensing measures the sum of metric potentials
  - Lensing power spectrum can only test specific models
- Lensing tomography ➡ how $D_{\psi+\phi}$ evolves with redshift
  - This is the primary test for dark energy models as well
- Relation of lensing observables to matter correlations ➡ $G_{effective}$
  - Provided there is a tracer of the mass with known bias
- Cross-correlations: galaxy-lensing plus galaxy-dynamics
  - Can give a model-independent measure of ϕ/ψ

Robust Test

Wide Field Lensing Surveys

- Ongoing: CFHT Legacy Survey
  - Ω_s=200 deg^2,n_g=30 arcmin^{-2}, *5 filters* ➡ Tomography

Future (start by ~2009+) surveys

- PanSTARRS1, KIDS, DES, Subaru…
  - DES telescope: 4m mirror, FOV 3 deg^2
  - Survey: *5000 deg^2* in 4-5 filters to ~24th magnitude (z~1).
  - Dark energy probes: Lensing, Galaxy clustering, Clusters, SN
  - Lensing measurements at few percent level from ~1-100 Mpc

Future (start ~2014+) surveys

- SNAP, DUNE, LSST
  - LSST telescope: 8.2 m diameter mirror, FOV 9.6 deg^2.
  - Survey: *Ω_s=20,000 deg^2* in 5-6 filters to *~26th mag* (z~2)

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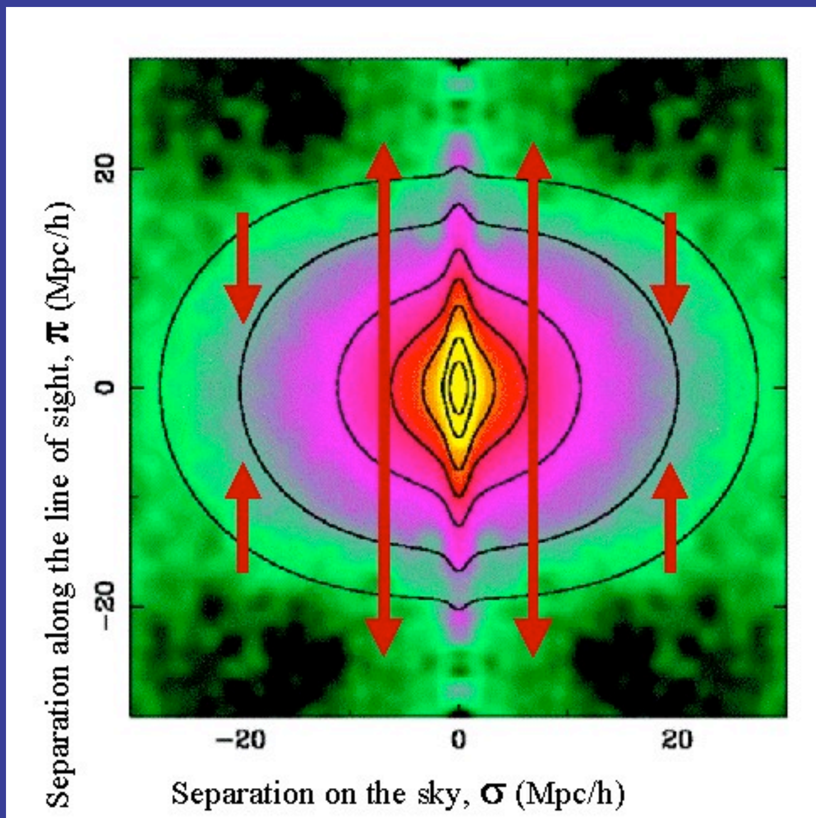
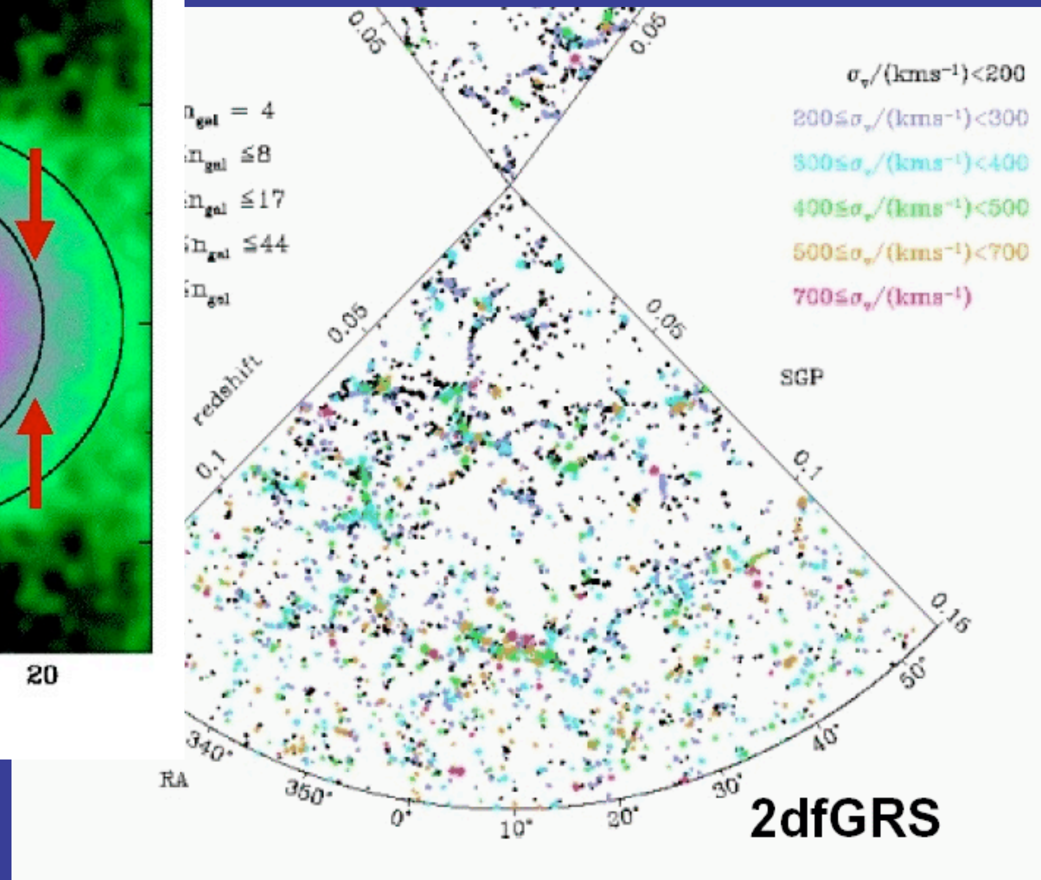
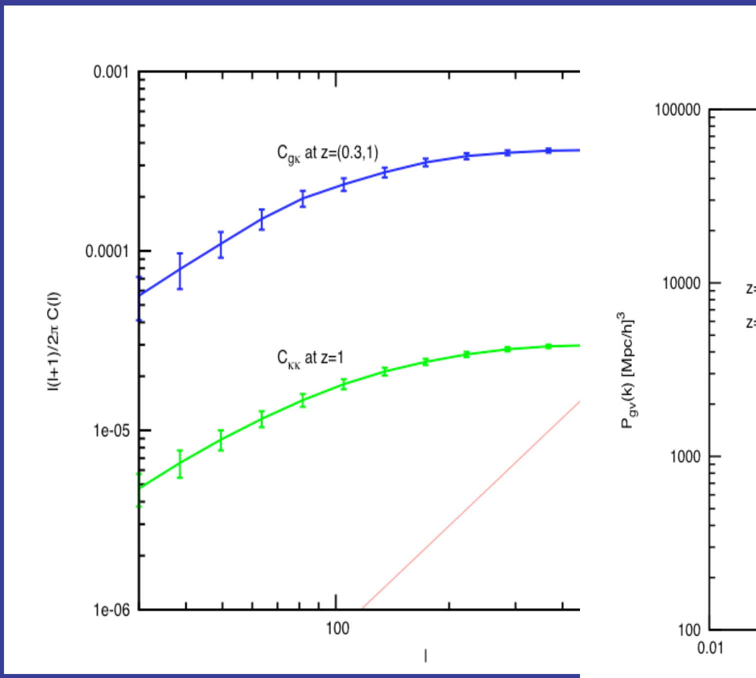
Redshift Space Distortions

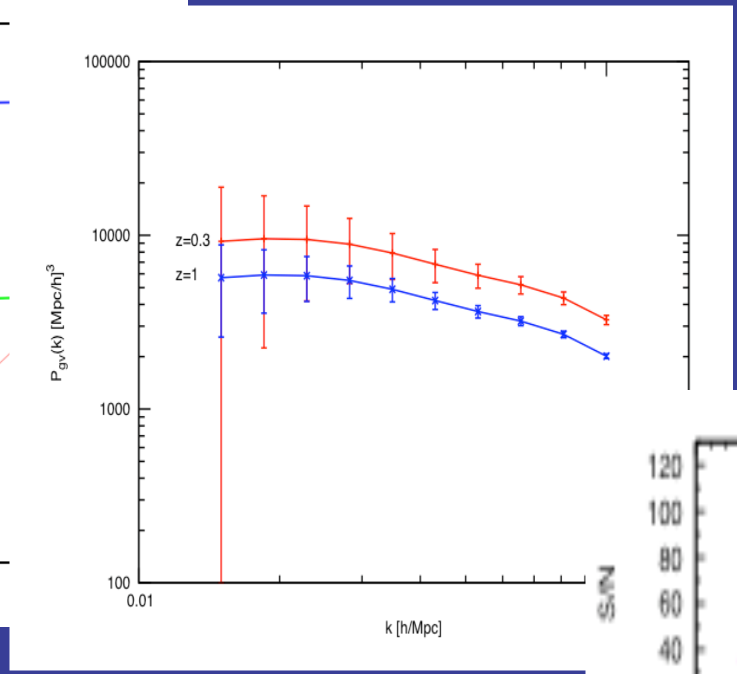


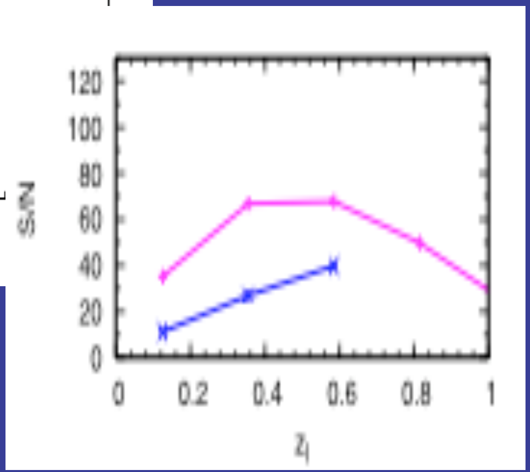


From redshift surveys, can measure three different power spectra

Lensing and Redshift Space Power Spectra

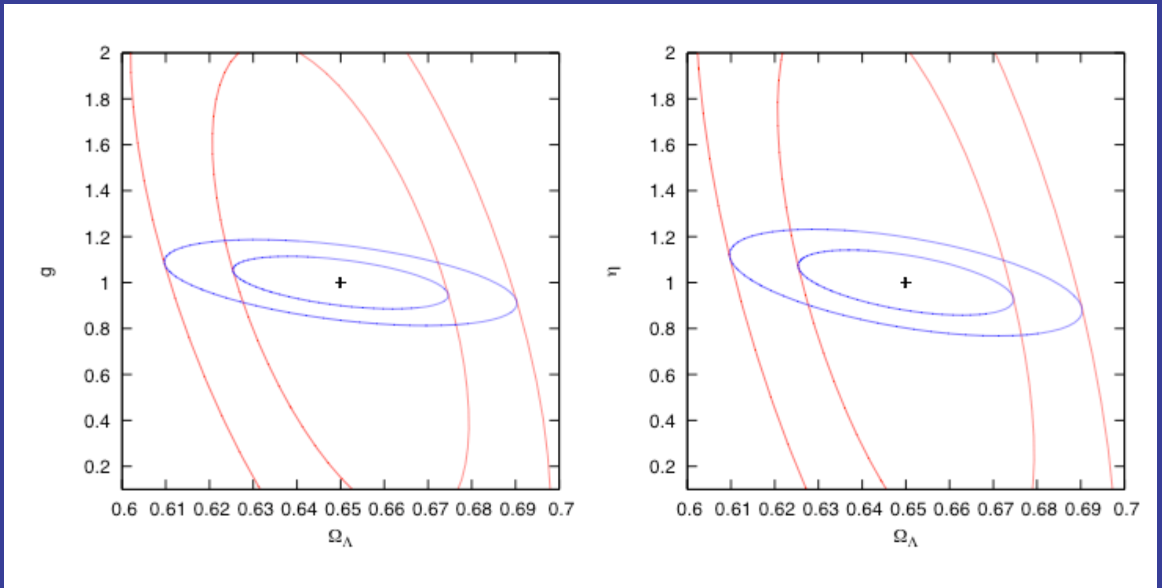




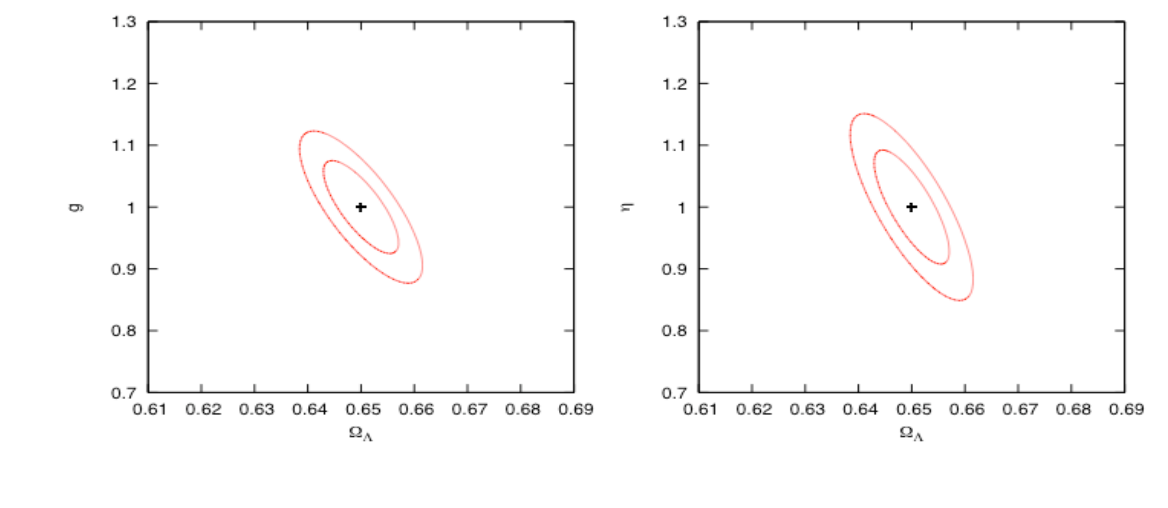


Expected measurements from upcoming surveys. *Guzik, Jain, Takada, in preparation*

Preliminary Forecasts for G,η



DES(5000) [red] -> DES(5000)+BOSS(10000) [blue]



Observational prospects for LSS tests

- For robust modified gravity tests, want potentials and density and velocity information at the same scale and redshift.

- Redshift $z \sim 0.3\text{-}1$ and $\lambda \sim 1\text{-}200$ Mpc for next generation surveys (~5 years).

- $P_{\gamma\gamma}$, $P_{g\gamma}$, P_{gg} measurable to ~ few percent accuracy with DES/Subaru/PS1 (sub-percent with LSST/EUCLID/JDEM)

- P_{gv} will be at 5-10% accuracy with spectroscopic surveys like BOSS; sub-percent accuracy with next generation surveys like SKA

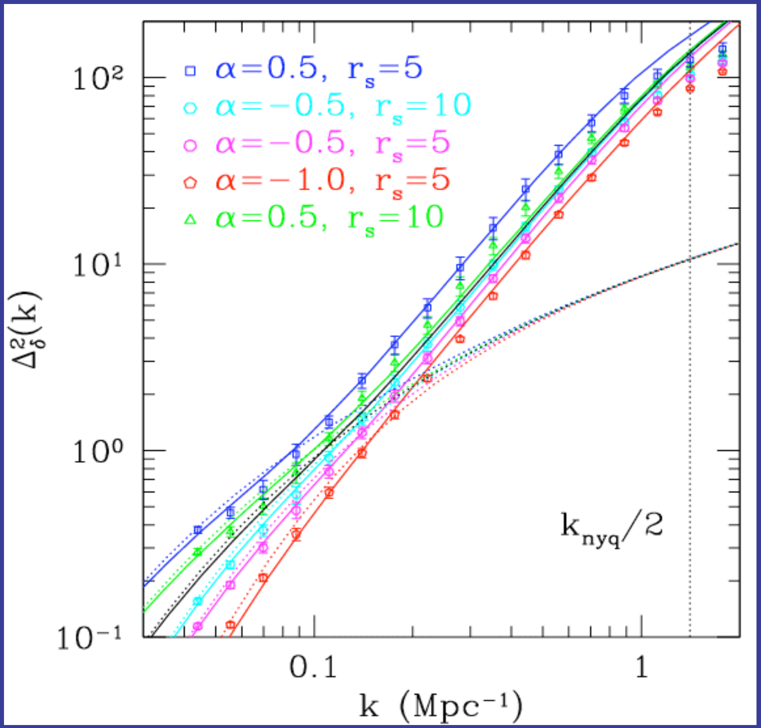
- Several other probes such as ISW may not reach percent level accuracy, but provide useful complementary information

Jain & Zhang 07; Zhang et al 07; Percival & White 08

Nonlinear Regime

- Small scale regime may provide best tests of gravity
- Theoretical predictions are specific to models and are difficult! But for f® type models some simplifications hold:
- Nonlinear power spectrum for "simple" modified gravity can be predicted using the linear power spectrum + nonlinear mapping tested for GR
- And in the quasilinear regime, the bispectrum can be obtained from linear power spectrum to better than a few %

Borisov & Jain 2008



Stabenau & Jain 2006
Shirata et al 2007; Laszlo & Bean 2008
Oyzaizu, Lima, Hu 2008: Chameleon regime

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Galaxy and Cluster Scales: Four Tests

- A. r~10 kpc: Einstein Rings + Stellar velocity dispersion
- B. r~100 kpc: Galaxy-galaxy lensing + Satellite dynamics
- C. r~1-10 Mpc: Cluster-galaxy lensing + Dynamics
- D. r~1 Mpc: Individual cluster masses from dynamics and weak lensing

Statistical Measurement

Halos: 101.2

•***Lensing***: Einstein Rings, Shear, Magnification:
Measures ($\phi+\psi$). Relation to mass involves Poisson eqn.

•***Dynamics***: Velocity dispersion, Rotation, Infall:
Measures Newtonian potential ψ

$M_{lensing} = (1+\gamma)/(2\gamma)\, M_{dynamics}$, $\gamma = \psi/\phi$

•If we use the same set of galaxies, can compare halo dynamics and lensing without needing the relation of galaxies to host halos.

•Cosmologists would talk about cross-power spectra (and insensitivity to bias factors): natural extension to large scales.

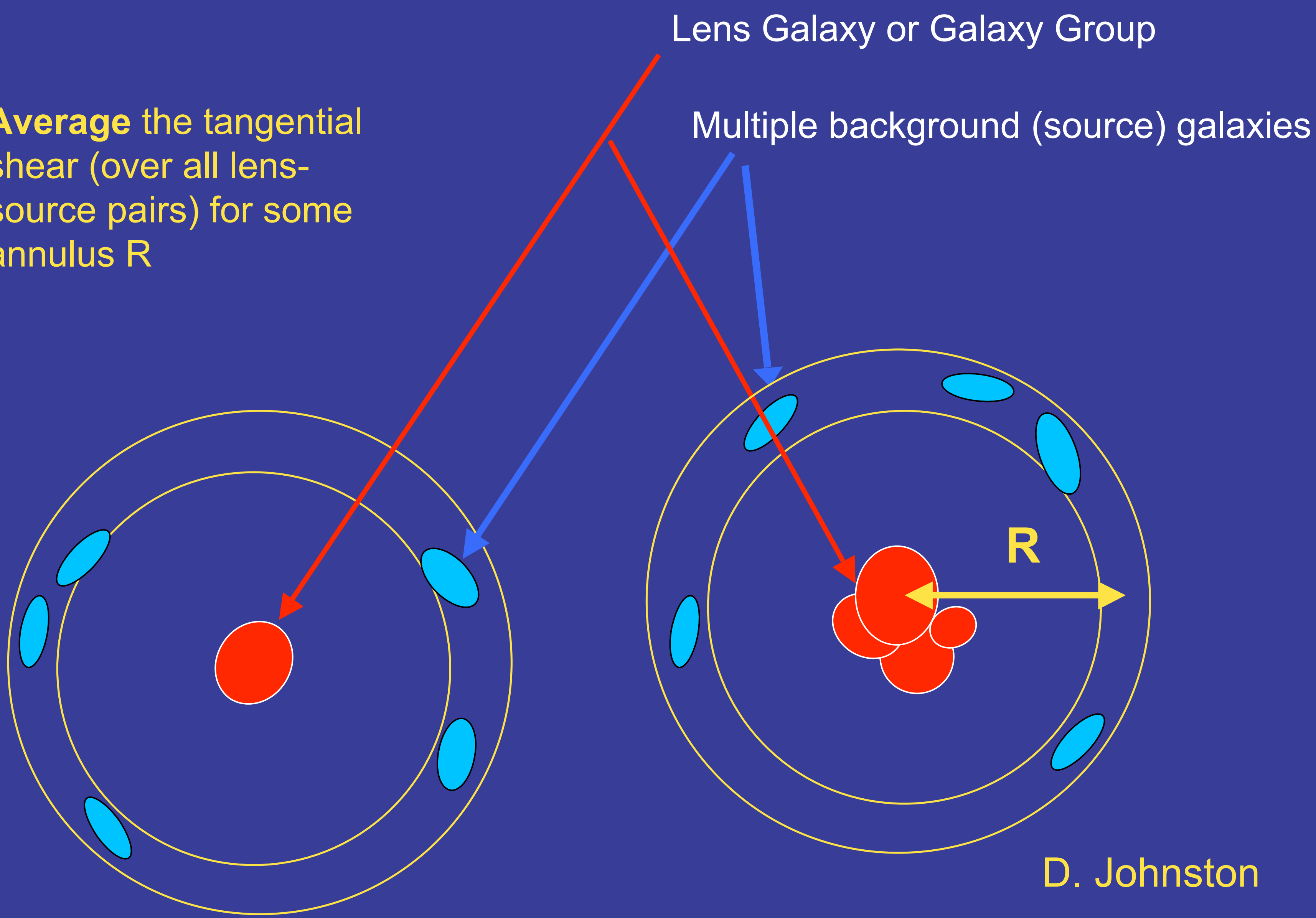
A. Galaxies: r~1-10 kpc

$\gamma = \psi/\phi = 0.98 \pm 0.07$ from SLACS Einstein Rings + velocity dispersion

Bolton et al 2006; Remodeling of the dynamics, in preparation!

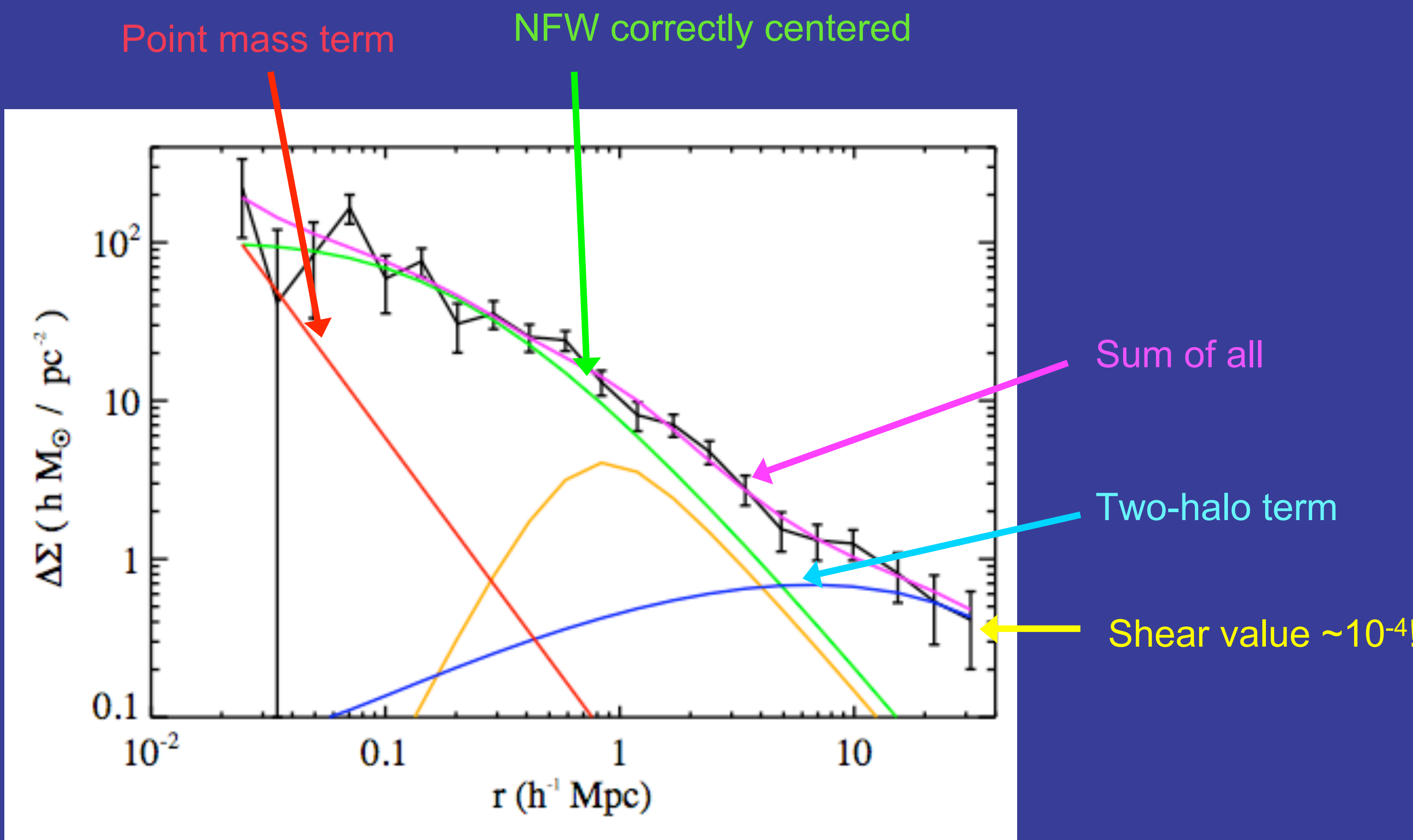
Galaxy-galaxy lensing

Average the tangential shear (over all lens-source pairs) for some annulus R



D. Johnston

Galaxy-galaxy lensing



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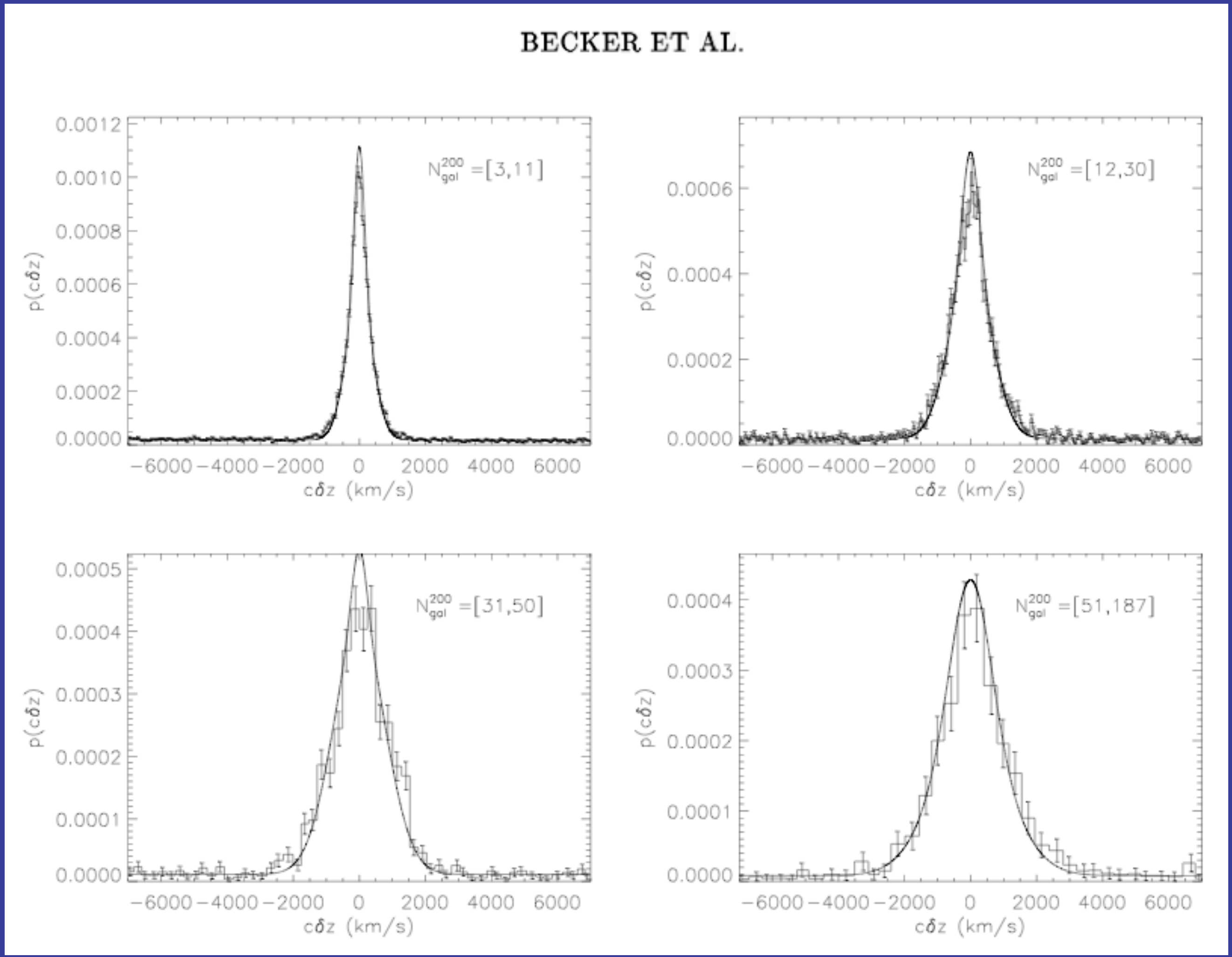
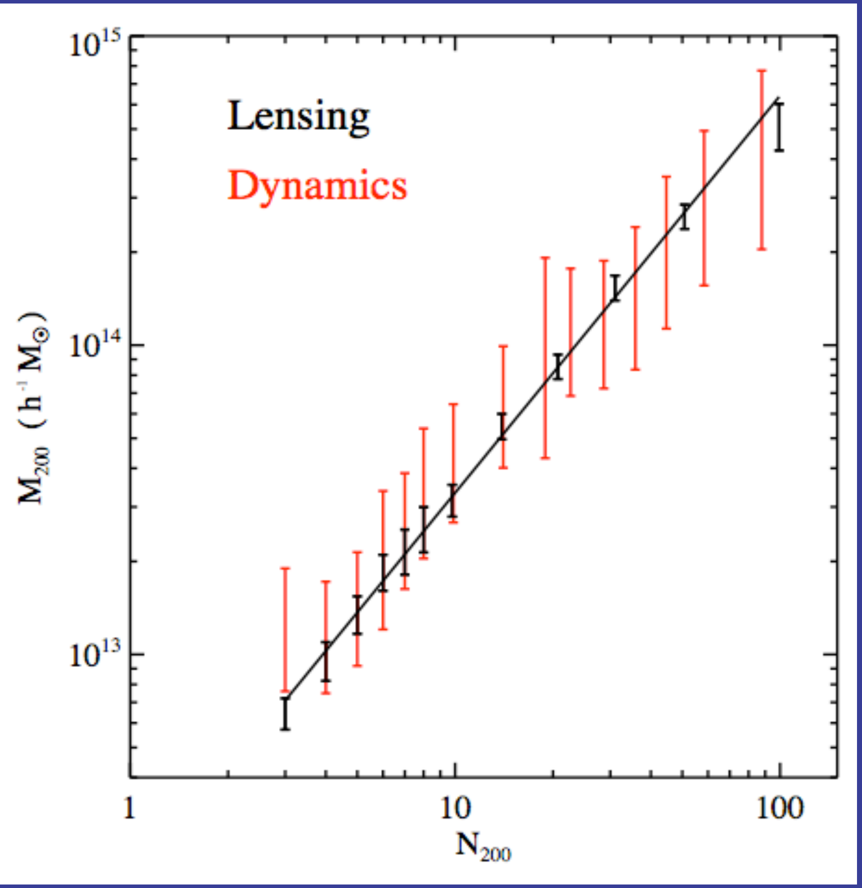
C. Group/Cluster Masses: Dynamical



•Stack velocity differences of satellite galaxies around BCG

•Richer clusters ➡ wider velocity histograms ➡ higher mass

C. Group/Cluster: 1 Mpc test

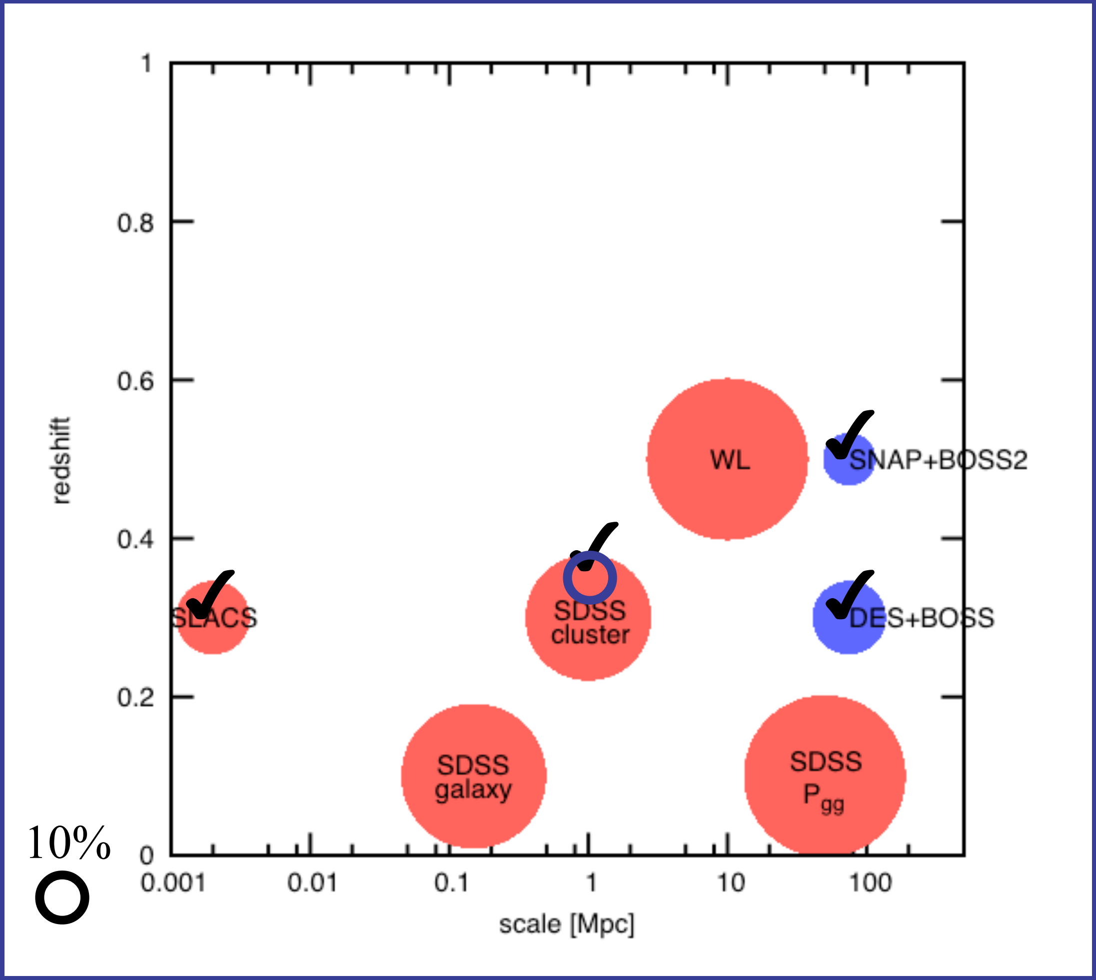


Sources of systematic errors:

- velocity bias
- velocity-to-mass error
- photo-z error
- shear calibration error
- mass modeling error

Johnston et al 2007

What do we know about gravity?



Errors on measurements of gravitational potentials and G

Red: current, Blue: future